AFRL-PR-WP-TP-2006-225

FLUX PINNING BEHAVIOR OF INCOMPLETE MULTILAYERED LATTICE STRUCTURES IN $YBa_2Cu_3O_{7-d}$

Paul N. Barnes, Timothy J. Haugan, Chakrapani V. Varanasi, and Timothy A. Campbell

APRIL 2006

Approved for public release; distribution is unlimited.

STINFO COPY

PROPULSION DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2006	Journal Article Postprint	05/20/2003 – 05/20/2004

4. TITLE AND SUBTITLE
FLUX PINNING BEHAVIOR OF INCOMPLETE MULTILAYERED LATTICE STRUCTURES IN $YBa_2Cu_3O_{7-d}$

5a. CONTRACT NUMBER In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 61102F/62203F

6. AUTHOR(S)
Paul N. Barnes, Timothy J. Haugan, Chakrapani V. Varanasi, and Timothy A. Campbell

5d. PROJECT NUMBER 3145

5e. TASK NUMBER 32

5f. WORK UNIT NUMBER 314532Z9

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Power Generation Branch (AFRL/PRPG)
Power Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-PR-WP-TP-2006-225

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7251

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-PR-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-PR-WP-TP-2006-225

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Journal article postprint published in Applied Physics Letters, Vol. 85, No. 18, November 1, 2004, published by American Institute of Physics.

PAO case number: AFRL/WS 04-0750; Date cleared: 01 Sep 2004. Paper contains color.

This is a work of the United States Government and is not subject to copyright protection in the United States.

14. ABSTRACT
Magnetization results of $YBa_2Cu_3O_{7-d}$ films processed with interlayers of CeO_2 inclusions are presented. Unexpected flux pinning results that are different from previous observations with nanoparticulate layered inclusions were observed. Flux pinning was found to be in some cases either slightly improved at either low fields <0.5 T or in other cases at high fields >8 T although degraded, sometimes severely, at interim magnetic fields. Most unexpectedly, the pinning performance of the various samples rapidly converges as the temperature is reduced from 77 to 65 K, causing all films to have similar J_c (H) behavior at 65 K even though dramatically different at 77 K.

15. SUBJECT TERMS
flux pinning, lattice structures, YBCO, superconductor

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	10	Paul N. Barnes / N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 18 1 NOVEMBER 2004

Flux pinning behavior of incomplete multilayered lattice structures in $YBa_2Cu_3O_{7-d}$

Paul N. Barnes,[a)] Timothy J. Haugan, Chakrapani V. Varanasi, and Timothy A. Campbell
Propulsion Directorate, Air Force Research Laboratory, Wright-Patterson AFB, Ohio 45433

(Received 20 May 2004; accepted 26 August 2004)

Magnetization results of $YBa_2Cu_3O_{7-d}$ films processed with interlayers of CeO_2 inclusions are presented. Unexpected flux pinning results that are different from previous observations with nanoparticulate layered inclusions were observed. Flux pinning was found to be in some cases either slightly improved at either low fields <0.5 T or in other cases at high fields >8 T although degraded, sometimes severely, at interim magnetic fields. Most unexpectedly, the pinning performance of the various samples rapidly converges as the temperature is reduced from 77 to 65 K, causing all films to have similar $J_c(H)$ behavior at 65 K even though dramatically different at 77 K. [DOI: 10.1063/1.1809274]

$YBa_2Cu_3O_{7-d}$ (YBCO) superconductor films are being developed for a variety of applications since high critical current densities (J_c) are maintained in applied magnetic fields of a few tesla. Even though YBCO has good in-field properties, it is of interest to further improve upon this characteristic by incorporating additional flux pinning sites in the YBCO. The intrinsic mechanisms of flux pinning typically occurring in as grown YBCO films are not immediately evident since the coherence length for this high temperature superconductor is quite small, $\xi \sim 1.5-2$ nm.[1,2] Because of the small coherence length, a variety of atomic size structures or defects in the film can pin the fluxons.[2] The small coherence length suggests that a high density of nano-sized insulating particulates dispersed throughout the superconductor can be an effective pinning structure potentially providing a greater pinning force than these intrinsic mechanisms.

Indeed, a method has been reported by Haugan *et al.* to incorporate nanoparticulate dispersions using pulsed laser deposition into YBCO films.[3,4] This was accomplished by the subsequent deposition of YBCO (5–25 nm thick) on top of nonsuperconducting Y_2BaCuO_5 (Y211)) island-growth particles ($\sim$5–10 nm in diameter) dispersed on the previously deposited YBCO layer. The layering was repeated to provide the desired thickness of the composite film, usually 0.3–3 μm thick. Y_2O_3 has also been incorporated in this same fashion with effective pinning.[5] However, data presented here using lattice matched interlayers of CeO_2 provide results that are not readily explained.

Relevant issues regarding the enhancement of pinning and its degradation include: multilayered structures or superlattices, particulate density, particulate size, and displacement of nanoparticulate layers (or, conversely, the thickness of the YBCO nanolayers). In previous multilayered structures, the interlayers were intentionally made continuous and often thick. Regarding particulate density, the higher the density the more fluxons that can be pinned, but a loss in superconducting volume will occur. The size of the particulates should approach a couple times the coherence length.[2] The separation between layered nonsuperconducting nanoparticulate inclusions can lower the effective pinning of fluxons, although pinned YBCO samples with layers up to 50 nm thick separating the nonsuperconducting inclusions still showed no significant decrease in effective pinning (largest thickness not yet determined).

Samples were prepared by pulsed laser deposition. A Lambda Physik laser, model LPX 305i, was used at 248 nm, the KrF wavelength. The ablation spot size was $\sim$6.5 mm^2. The oxygen deposition pressure was 300 mTorr kept constant by downstream flow control while O_2 gas flowed at $\sim$1 l/min. Single crystal substrates of strontium titanate (STO) were attached to the heater using a thin layer of colloidal Ag paint. The heater temperature during deposition was 750 °C. Substrates sizes were approximately 3.2 $\times$3.2 mm^2. The films were oxygen annealed after deposition by gradually cooling the samples in oxygen gas.

To create the multilayer structures, deposition of YBCO was done first for 195 pulses at a 4 Hz rate which results in a $\sim$11-nm-thick film. A CeO_2 target was then rotated into place and several pulses of the laser were applied as specified in Table I. The YBCO target was then rotated back into place and the cycle repeated until $\sim$0.3-μm-thick composite films were made. The sequential PLD depositions were automated by computer control. Film growth was stopped between each layer while the other target was rotated into position. The Y211 and Y_2O_3 particulate inclusions referred to were created in the same manner with use of the respective target in lieu of the CeO_2 at 780 °C. The experimental conditions used to create CeO_2 islands in YBCO samples are listed in Table I.

To determine the resulting pinning effect, samples were mounted in a vibrating sample magnetometer. The samples

TABLE I. Experimental conditions used to grow CeO_2 islands in YBCO films.

Sample	Energy (mJ)	Rep rate (Hz)	Dep time (s)	Pulses (total No.)
1	511	4	3.75	15
2	511	2	4.5	9
3	196	2	4	8
4	196	4	3	12
5	196	2	2.5	5

[a)]Electronic mail: paul.barnes@wpafb.af.mil

0003-6951/2004/85(18)/4088/3/$22.00 4088

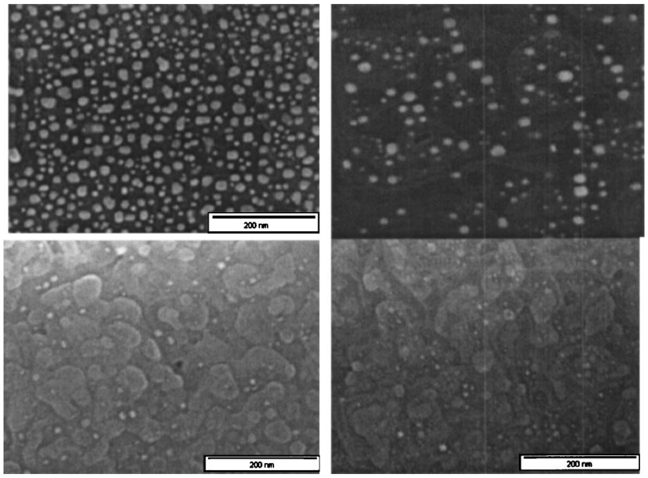

FIG. 1. Scanning electron micrographs of the surface following deposition on YBCO of Y_2O_3 (upper SEMs) and CeO_2 (lower SEMs).

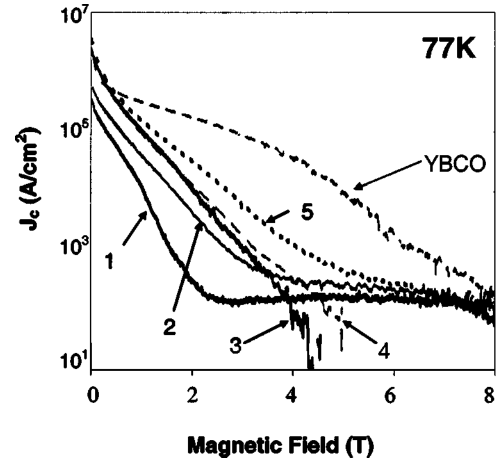

FIG. 2. J_c vs applied magnetic field at 77 K for the samples with CeO_2 islands.

were mounted such that the field was applied perpendicular to the wide face of the sample with currents induced in the $a-b$ planes of the HTS films. $M-H$ loops were obtained collecting data every second with a 100 Oe/s ramp rate and vibration frequency of 40 Hz. The resulting $M-H$ loops were volume normalized and then the magnetization critical current density (J_c) was determined using Bean's model $J_c = 30\ \Delta M/d$, where ΔM is the hysteresis loop width and d is the average sample size in the film plane. The onset superconducting transition temperature (T_c) was measured using an ac susceptibility technique with the amplitude of the magnetic sensing field varied from 0.025 to 2.2 Oe, at a frequency of approximately 4 kHz.

The films were of good quality as determined from ac susceptibility. T_c for the samples were 88–90 K, which is slightly depressed from plain YBCO (T_c of 90–92 K) using the same processing conditions. This is typical of all previous nanoparticulate layering. The spread of the magnetic field lines in the ac loss data were narrow indicating good films and showed a sharp single phase transition. Self-field J_c values of most samples were high >1 MA/cm^2.

An initial deposition of CeO_2 resulted in almost complete planar inclusions of $\sim$2–3 nm thick within the YBCO layer. In this case, in-field pinning was severely degraded compared to plain YBCO and pinning by Y211 nanoparticles, although self-field values of each are comparable. This can be ascribed to the nature of the pancake vortices within the high temperature superconductor copper-oxide planes being weakly coupled together. The CeO_2 interlayers help decouple the vortices degrading pinning. Lower deposition times of CeO_2 were used to avoid a continuous layer; however, the size of inclusions is affected more by the lattice matching of the nonsuperconducting inclusions to YBCO and the pinning density by length of deposition. Figure 1 shows the difference between Y_2O_3 nanoparticle inclusions (upper) and that of the larger nanopatches of CeO_2 (lower) for longer (left) and shorter (right) deposition times. It can be seen that Y_2O_3 particles are much smaller as compared to CeO_2 inclusions. Y211 inclusions in a separate study showed slightly smaller particle formation than Y_2O_3 likely due to a different growth mechanisms based on lattice mismatch.[3,4]

With the CeO_2 patchwork interlayers, it is expected the pinning will be less due to the large size of the inclusions (see Fig. 2). However, significant exceptions occur in the resulting data for the nanopatches of CeO_2 at either very low or very high fields. At fields greater than 8 T, three CeO_2/YBCO samples match plain YBCO and Y211/YBCO sample performance and appear to become better although not clear. In other samples minor improvement over YBCO occurred for <0.5 T. Generally, samples fell into the category of low field improvement, high field improvement, or no improvement. All films displayed severely degraded performance at moderate magnetic fields. Of greater interest is the difference in temperature dependence of the CeO_2/YBCO samples. Figure 3 shows the field dependence at 65 K. In-field performance rapidly converges together at this temperature for all CeO_2/YBCO specimens, even losing the high field advantage of the two samples. This is contrary to typical YBCO and nanoparticulate pinning by Y211 or Y_2O_3. The natural assumption is that the CeO_2 nanopatches result in decoupling of many of the pancake vortices in the YBCO degrading pinning, but this does not explain the unexpected behavior. Also, the high self-field performance of most samples indicates that the chemical degradation due to barium cerate formation is not significant. Potential doping of the superconductor in combination with the nanolayered structure may be possible.[6]

In conclusion, the use of CeO_2 in interlayer inclusions within YBCO provide unexpected flux pinning behavior. In some samples, pinning improvement over plain YBCO oc-

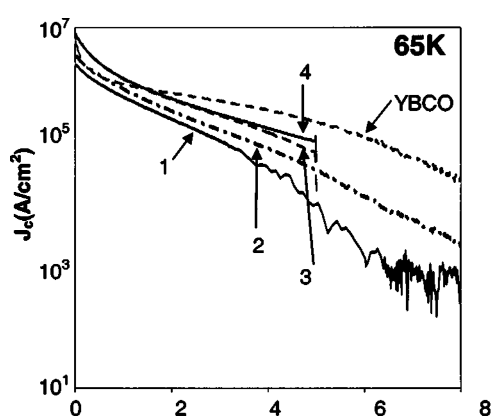

FIG. 3. J_c vs applied magnetic field at 65 K for the samples with CeO_2 islands.

curred at low fields, <0.5 T, and in others with apparent improved pinning observed at high fields >8 T while J_c is severely degraded at moderate fields. Most significant is that the pinning performance of the various samples rapidly converges as the temperature of measurement is lowered, with all CeO_2/YBCO films behaving similarly at 65 K even though substantially different at 77 K.

[1] J. Talvacchio, IEEE Trans. Compon., Hybrids, Manuf. Technol. **12**, 21 (1989).
[2] D. Larbalestier, A. Gurevich, D. M. Feldmann, and A. Polyanskii, Nature (London) **414**, 368 (2001).
[3] T. J. Haugan, P. N. Barnes, I. Maartense, E. J. Lee, M. D. Sumption, and C. B. Cobb, J. Mater. Res. **18**, 2618 (2003).
[4] T. J. Haugan, P. N. Barnes, R. Wheeler, F. Meisenkothen, and M. Sumption, Nature (London) **430**, 867 (2004).
[5] T. A. Campbell, T. J. Haugan, L. Brunke, P. N. Barnes, J. W. Kell, I. Maartense, S. Sathiraju, J. P. Murphy, and J. C. Tolliver, 106th Annual Meeting of the American Ceramic Society, 2004; T. A. Campbell, T. J. Haugan, I. Maartense, J. Murphy, L. Brunke, and P. N. Barnes, Physica C (accepted for publication).
[6] C. Varanasi, R. Biggers, I. Maartense, D. Dempsey, T. L. Peterson, J. Solomon, J. McDaniel, G. Kozlowski, R. Nekkanti, and C. E. Oberly, *Advances in Laser Ablation of Materials*, edited by R. K. Singh, Dh. Lowndes, D. B. Chrisey, E. Fogarassy, and J. Naraya (Materials Resource Society, Warrendale, PA, 1998), pp. 263–268.